

AN OVERVIEW OF NASA'S MARS SCIENCE LABORATORY

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ABSTRACT

This paper provides a high level overview of NASA's Mars Science Laboratory. Topics to be explored are the Mission's science goals and objectives, a discussion of the mission phases, an overview of the flight system architecture and the payload, and a discussion of the MSL power system.

1. GOALS AND OBJECTIVES

The Mars Science Laboratory (MSL) shares the four overarching science goals of NASA's Mars Exploration Program: Determine whether life ever arose on Mars, characterize the climate on Mars, characterize the geology of Mars, and prepare for human exploration. In addition, MSL has the specific goal of determining the habitability of Mars [1]. From these goals, MSL has defined eight scientific objectives, broken up into four core areas: Biological, geological and geochemical, planetary processes, and surface radiation.

MSL's biological objectives for verification of past or present habitability include the determination of "the nature and inventory of organic carbon compounds," an accounting of "the building blocks of life" inclusive of "carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulphur," and the identification of Martian properties that "may represent the effects of biological processes [1]." The geological and geochemical objectives of MSL are to "investigate the chemical, isotopic and mineralogical composition of the Martian surface and near surface geological materials," and to "interpret the processes that have formed and modified rocks and soils [1]." The mission's planetary process objectives are to "assess long timescale (four billion year) atmospheric evolution processes" and "determine present state, distribution, and cycling of water and carbon dioxide [1]." Finally, the surface radiation objective is to "characterize the broad spectrum surface radiation, including galactic cosmic radiation (GCR), solar proton events, and secondary neutrons [1]."

In addition to the science objectives, MSL has two technology objectives; the demonstration of improved landing precision through the use of guided entry, and the demonstration of a landing system capable of accessing a significant fraction of the surface of Mars.

2. MARS SCIENCE LABORATORY REQUIREMENTS

The objectives and goals of MSL lead to a subset of Project Level 1 requirements that are the critical design drivers. This subset requires that MSL shall:

1. Be able to land at altitudes of up to +1 km (originally +2.0 km) relative to the MOLA aeroid.
2. Be capable of landing and operating at sites between 45°N and 45°S latitude.
3. Be able to land with an error of 10 km or less, radially, from a designated point on the surface of Mars (excluding any uncontrolled effects utilizing a guided atmospheric entry).
4. Accommodate the NASA selected payload.
5. Provide data communication throughout critical events (Entry, Descent and Landing) at a rate sufficient to determine the state of the spacecraft in support of fault reconstruction.
6. Acquire scientific data about the rover's local region and conduct mobile *in situ* analysis with the rover and its scientific payload for at least one Martian year.
7. Deliver to Mars a rover with the capability of a total traverse path length of at least 20 km.
8. The project system shall be able to select, acquire process, distribute, and analyze at least 74 samples of rock, rock fragments, and/or regolith.

It will become apparent how these requirements drive the mission design and system architecture employed to implement MSL in the sections that follow.

3. LAUNCH, CRUISE AND APPROACH

MSL's journey to Mars commences during its launch opportunity of November 25th, 2011 through December 18th, 2011. The launch will occur from Cape Canaveral Air Force Base on an Atlas V 541 having a 5.4 meter fairing, four solid rocket boosters and a Single-Engine Centaur (SEC) upper stage [2]. Launch begins the journey of MSL to its Martian destination. At release from the SEC, the spacecraft is spin stabilized at a rate of two revolutions per minute (RPM). The interplanetary path to Mars can be seen in Fig. 1 [3].

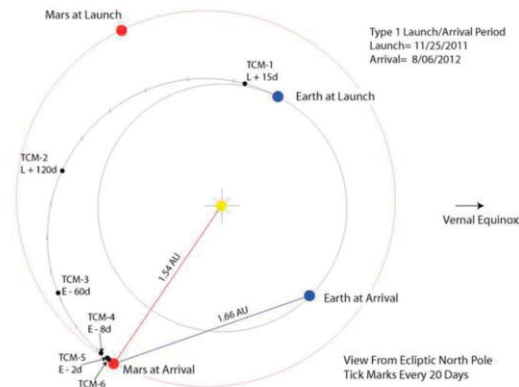


Figure 1. MSL Interplanetary Trajectory [3].

The interplanetary travel portion of the mission consists of the Cruise and Approach phases, together lasting approximately 250 days. There are six Trajectory Correction Maneuvers (TCM) planned before the beginning of the Entry, Descent and Landing (EDL) Phase of the mission. Three TCMs are planned in the Cruise Phase and three are planned in the Approach Phase. The TCM description and relative execution time with respect to launch can be found in Tab. 1. The Approach Phase comprises the 45 days just prior to EDL. The sole purpose of this phase is to minimize any deviations from insertion to the required aimpoint and to guarantee that the EDL sequence parameters are loaded onto the spacecraft [3].

Table 1. MSL TCM Summary [3].

TCM	Maneuver Time	Description
TCM-1	Launch + 15 days	Correct injection errors; remove part of injection bias required for planetary protection
TCM-2	Launch + 120 days	Correct TCM-1 errors; remove part of the injection bias required for planetary protection
TCM-3	Entry - 60 days	Correct TCM-2 errors; target to desired atmospheric entry aimpoint
TCM-4	Entry - 8 days	Correct TCM-3 errors
TCM-5	Entry - 2 days	Correct TCM-4 errors
TCM-5X	Entry - 1 day	Contingency maneuver for failure to execute TCM-5
TCM-6	Entry - 9 hrs	Contingency maneuver: final opportunity to correct entry aimpoint

The injection bias required for planetary protection is referenced to maintain a low probability – less than 10^{-4} – of the Centaur Stage impacting Mars [3].

4. ENTRY, DESCENT AND LANDING

The MSL EDL System needs to be capable of landing a large mass at a high Martian altitude, of at least 0 km above the Mars Observer Laser Altimeter (MOLA) aeroid, be capable of landing at Martian latitudes of between 45°N and 45°S , and be able to land the system within a 10 km landing ellipse. These have driven the EDL System to be capable of high precision and accuracy and to be capable of landing a system with

decreased aerodynamic drag due to the required increased elevation relative to other missions. It is easy to see that these requirements were designed to allow for an increased choice of MSL landing sites, including sites previously not accessible to NASA Landers.

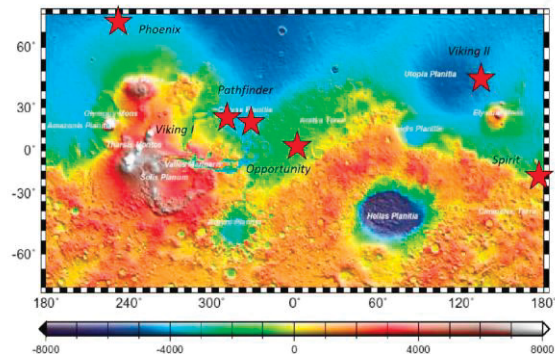


Figure 2. MOLA Aeroid and Past NASA Landing Sites.

The EDL Phase begins immediately following the Approach Phase. The EDL timeline consists of five stages; Entry, Parachute Descent, Powered Descent, Sky Crane and Flyaway (Fig. 3 [3]). Requirements have also driven the system to transmit X-band tones direct to Earth to notify MSL operators of successful EDL events. More-detailed EDL information is also transmitted over UHF at 8 kbps to Mars orbiting assets.

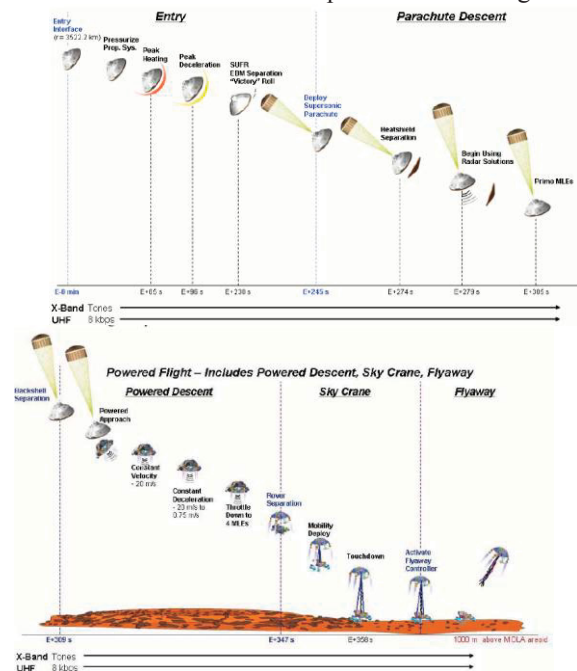


Figure 3. The Stages of EDL. [3].

Just before Entry, the Cruise Stage Heat Rejection System (discussed in detail later) is vented and the Cruise Stage separates from the descent system. During “Entry”, which lasts 245 seconds, the Descent Stage Propulsion System is pressurized and the system undergoes peak aerodynamic heating and deceleration.

The system enters “Parachute Descent” between Mach 1.8 and Mach 2.2, at which point the parachute deploys [3]. Once the velocity decreases into the range of Mach 0.5—0.8, the heat shield is released [3]. At this point (Entry +279 seconds) the Terminal Descent Sensor (TDS) on the Descent Stage begins measuring altitude and velocity [3]. Just before Powered Descent begins, surface relative navigation by the MSL Descent Stage (discussed in Section 5) is operating and the Mars Landing Engines (MLE) of the Descent Stage Propulsion System are ignited.

Backshell separation marks the beginning of “Powered Descent” and is expected to occur between 1500 and 2000 meters [3]. The MSL Descent Stage brings the relative velocity of the system from 20 m/s at backshell separation to a constant 0.75 m/s [3]. Once the Descent Stage reaches an altitude of 18.6 meters, with a constant vertical velocity of 0.75 m/s and a horizontal velocity of 0 m/s, the system transitions to “Sky Crane” and the Rover is lowered by a triple-bridle to a length of 7.5 meters [3].

While descending under the Descent Stage, the triple-bridle is monitored for persistent measurement of offloading, estimated to occur at Entry +358 seconds. Once offloading is detected, the MSL Descent Stage hovers in position while the Rover cuts the triple-bridle [3]. Once the bridle is cut, the Descent Stage enters “Flyaway” and maintains constant thrust and attitude so as to land (uncontrolled) on the Martian Surface at least 150 meters away from the Rover’s landed position [3].

5. THE MSL FLIGHT SYSTEM

In order for MSL to carry out the mission set forth by NASA, a very ambitious architecture was created. The MSL system consists of four main constituents; the cruise stage, the aeroshell (inclusive of the heat shield), the descent stage, and the rover (Fig. 4).

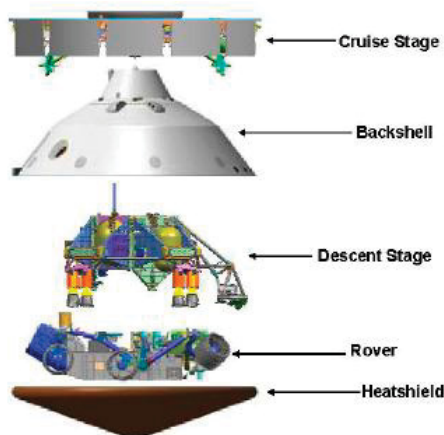


Figure 4. Mars Science Laboratory Flight System. [4]

To simplify the development as much as possible, shared designs in avionics, power, pyro and propulsion, and telecom have been used in the implementation.

5.1. The MSL Cruise Stage

Six subsystems or portions thereof, comprise the Cruise Stage (CS) of MSL. These subsystems and assemblies include:

1. Cruise Guidance, Navigation and Control (GN&C) Sensors.
2. Cruise Heat Rejection System (CHRS)
3. Cruise Mechanical Structure
4. Cruise Power
5. Cruise Propulsion
6. Cruise Telecommunications Antennas

The CS GN&C sensors, along with the Descent Inertial Measurement Unit (DIMU) in the Descent Stage (DS) and the Rover Inertial Measurement Unit (RIMU) in the Rover, are used to acquire attitude information about the spacecraft during the cruise phase of the Mission.

The CS-mounted GN&C sensors include the Digital Sun Sensor Assembly (DSA) and the Star Scanner Assembly (SSA.) The DSA is used to monitor two-axis solar aspect data and provide coverage of the axes missing from the SSA data. It consists of eight Digital Sun Sensor Heads (DSHs) and redundant Digital Sun Sensor Electronics (DSEs). Each DSH has $\pm 128^\circ$ Field of View (FOV) providing for full sky coverage except for an 11° cone about the $+Z$ -axis. The configuration of the DSHs and DSEs is two strings consisting of 4 DSHs and a single DSE. Three DSHs of each string are configured around the circumference of the Cruise Stage and pointing slightly to the $-Z$ -axis, with the forth aligned with the $-Z$ -axis (nominally aimed towards the sun in cruise) [4].

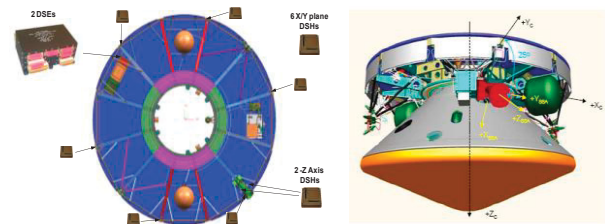


Figure 6. Cruise Stage DSA and SSA Configuration.

The SSA consists of a single star scanner mounted to the edge of the cruise stage providing roll position information about the spacecraft (Fig. 6.)

The Cruise Heat Rejection System (CHRS) is a mechanically pumped fluid (Freon/CFC-11) heat exchange system used to maintain the temperatures of the various assemblies and subsystems of MSL within their predefined Allowable Flight Temperatures (AFTs) [5]. This is done through heat removal/cooling of the

The CS Power hardware consists of the Cruise Power Assembly (CPA), the Cruise Pyro-Firing Assembly (CPFA), the Cruise Power Analog Module (CPAM), and the solar arrays. These are discussed further below.

The majority of the telecom hardware resides on the Descent Stage and the rover. The only piece of hardware from the telecom subsystem located on the CS is the Cruise Stage X-band Medium Gain Antenna (CMGA).

5.2. The Entry and Descent Vehicle

The Entry Vehicle and the Descent Stage are two configurations of MSL used during the stages of EDL, to deliver the Rover to the surface of Mars. The Entry Vehicle and Descent Stage configurations are shown in Fig. 7.

Except for computer control provided by the dual-redundant Rover Compute Elements (RCE) and The Electra-Lite UHF Transponder, the EDL system functions are carried out by the subsystems resident in whole or in part on the Aeroshell, the Heat Shield, and the Descent Stage. The Equipment carried includes:

1. Descent Inertial Measurement Unit (DIMU)
2. Descent Motor Control Assembly (DMCA)
3. Descent Power Assembly (DPA)
4. Descent Power Analog Module A/B (DPAM)
5. Descent Propulsion System (DPS)
6. Parachute.
7. Power Bus Thermal Batteries (Main and Redundant)

8. Pyro Bus Thermal Batteries (Main and Redundant)
9. Telecom
 - a. Small Deep Space Transponder (SDST)
 - b. Aeroshell
 - i. Parachute Low Gain Antenna (PLGA).
 - ii. Tilted Low Gain Antenna (TLGA)
 - iii. Descent Stage Low Gain Antenna (DLGA)
 - iv. Descent Stage UHF Antenna (DUHF)
10. Terminal Descent Sensor (TDS, Radar).

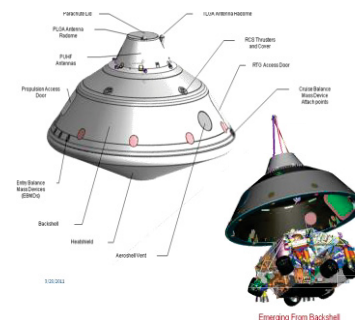


Figure 7. Entry Vehicle and Descent Stage Configuration.

The Descent Stage Avionics, Power and Propulsion hardware accommodation is shown in Fig. 8. Details of the power system hardware operation (DPAMs, DPA, DMCA and Thermal Batteries) are found in Section 6.

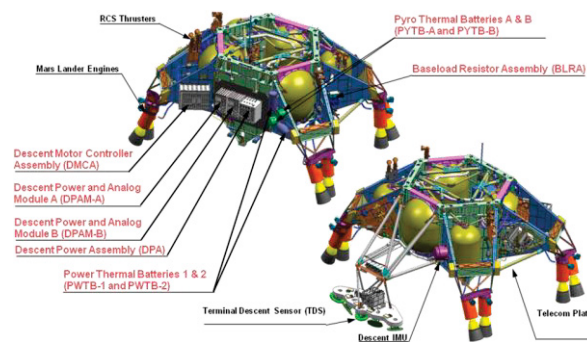


Figure 8. Descent Stage Avionics and Power Hardware Accommodation.

The operation of the system during EDL is carried out by both RCEs, run in hot redundancy, with support from the DIMU, DMCA, DPA, DPAM and Descent Propulsion System. The attitude information is taken from the DIMU and the TDS. The DIMU provides relative inertial measurements of the system and the TDS provides attitude and velocity measurements with respect to ground. The RCE uses this information to control the DPS consisting of the eight MLEs (throttle capability of 400—3060N), the eight RCS Thrusters (250N minimum,) two Helium gas pressurizing tanks, and three Hydrazine propellant tanks (Fig. 8.) The MLEs are controlled through the DMCA and the RCS Thrusters are controlled through the DPAM. Descent Stage pyro events, including release of the parachute are initiated through the DPA.

Throughout all phases of EDL there is a requirement that the system transmit data sufficient for the reconstruction of EDL failures if they should occur. Due to the various link geometries associated with guided entry, banking maneuvers, landing site latitudes and the certain occurrence of a plasma blackout on the UHF link, during EDL both X-band and UHF transmit continuously through several different antennas (Fig. 9.)

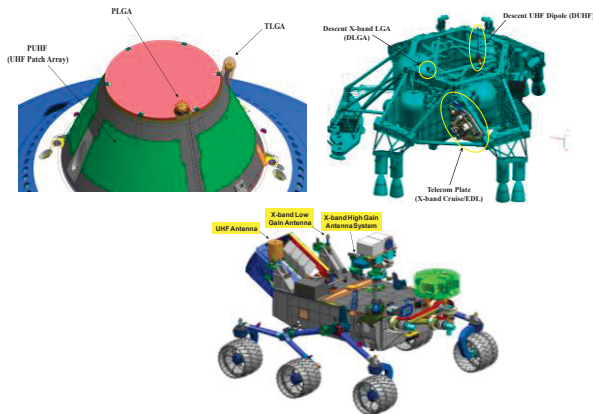


Figure 9. The Antennas of EDL.

X-Band communication is Direct to Earth (DTE) and uses semaphore tones to communicate the different portions of the EDL sequence. The 8 kbps UHF link communicates to orbiting assets, which in turn transmit the EDL data back to Earth.

At Cruise Stage separation, DTE and Relay communication commences using the SDST of the Descent Stage and the Electra-Lite UHF radio of the Rover. The antenna usage is as follows:

1. Cruise Stage Separation: PLGA for DTE and PUHF for Relay
2. Entry: TLGA for DTE and PUHF for Relay
3. Parachute Deploy: PLGA for DTE and PUHF for Relay.
4. Backshell Separation: DLGA for DTE and DUHF for Relay.
5. Rover Separation: DLGA for DTE and RUHF for Relay.

5.3. The Rover

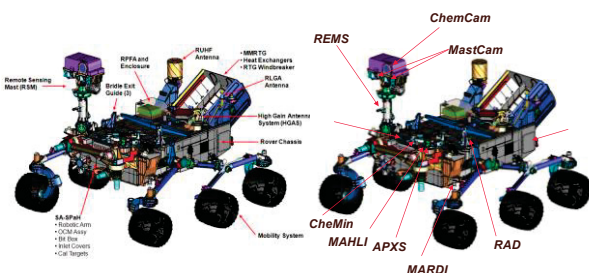


Figure 10. The MSL Rover

The MSL rover is the largest Rover built by NASA to date, standing 2.2m high at the top of the remote sensing mast (RSM) 2.77m wide at the wheels, with a 2.3m wheelbase, and a mass of approximately 930 kg. The rover is expected to be able to traverse at least 20km during its 670 sol lifetime (for comparison, as of this writing the MER-B Opportunity rover has traversed more than 26.7km during more than 2500 sols of operation.) The most notable design feature of the rover is the “rocker-bogie” suspension, developed at JPL to enable rovers to traverse difficult terrain and proven on the previous rovers. It has been considerably scaled up to match the much larger size of MSL. The rover is composed of several mechanical subassemblies: The mobility system consisting of the wheels and the rocker-bogie suspension; the main chassis housing the batteries, many of the instruments and most of the electronics; the sample acquisition/sample preparation and handling system (SA/SPaH); the MMRTG assembly mounted to the back of the chassis; and the Remote Sensing Mast (RSM.)

The rover compute elements (RCE) housed within the chassis are the “brains” of MSL in all mission phases. The RCE is dual redundant with one maintained as a cold (powered-off) spare except during EDL when the redundant RCE is powered on but on standby. The RCEs are based on a RAD750 processor (512Mb of RAM, 4Gb of flash, interfaced over a 33MHz PCI bus). It has a large number of interfaces to manage the instruments, as well as a 1553 serial bus to interface to the cruise and descent stages and the power and pyro system. In addition to providing command, control and data handling during surface operations, the RCE is also the spacecraft intelligence during cruise and EDL. The RCE also manages communications, and provides data storage for up to 100 sols worth of science data.

Communication from the rover to Earth is done by relay through the Mars Reconnaissance Orbiter (MRO) during two overhead passes per day. The system utilizes the Electra-Lite UHF transponder and is capable of sending 250Mbits/sol to Earth. MSL also has an X-band telecom system based on the Small Deep Space Transponder (SDST) demonstrated by the Deep Space 1 mission. The X-band system has both a pointing high-gain antenna, and a fixed omnidirectional low-gain antenna (Fig. 13.) Both are capable of direct-to-Earth communication (with the help of the deep space network) but because of very low bandwidth the low-gain antenna is only used for contingencies. Because of the high bandwidth and data volume requirements, relay through orbiters is the primary communication path.

Also housed in the chassis is the Rover Motor Control Assembly (RMCA), which switches power and provides closed-loop control for up to 48 motors, with up to eight motors operating simultaneously. Actuators are used throughout the rover for mast and camera pointing, for

robotic arm movement and turret rotation, for drilling, and for mobility. Each of the six wheels on the rocker bogie suspension has its own independently controlled drive motor. In addition, the two front and two rear wheels have independent steering motors to rotate the wheels for steering and traction.

The Rover uses several black and white cameras as part of its mobility system. Two Hazard avoidance cameras (Hazcams) are mounted at the base of the rover chassis both on the front and the rear, used to map the view ahead and behind to watch for obstacles and hazards. There are also two navigation cameras (Navcams) mounted on the RSM. The RSM is mounted on top of the rover, placing the Navcams at roughly the height of the human eye. The Navcams can be rotated around to survey the terrain, and pointed up and down for different views of the surface. These cameras can be used to create detailed 3D images of the terrain around the rover. The RSM also holds two other science experiments, the dual-camera imaging Mastcam and the laser-based ChemCam.

The SA/SPaH is the subsystem responsible for acquiring samples from the surface, processing the materials into particulates, and distributing them to the SAM and CheMin instruments. There are also two instruments mounted on the robotic arm (APXS and MAHLI) which must be placed in contact with surface samples such as rocks and soil to operate. The center of the SA/SPaH is the titanium five degree-of-freedom robotic arm mounted to the front of the rover chassis: The robotic arm is capable of extending 2.3 meters in front of the rover, accurately positioning 33kg of tools and instruments on the end-mounted turret. This complex arm is used to place sample gathering devices and instruments mounted on the turret into contact with targeted surface materials, to hold a drill/hammer in place while rock is drilled and pulverized, and to transport the collected materials to the instrument inlets located on the top of the rover chassis.

In addition to the two science instruments, the turret also has three devices for actively acquiring surface samples. These consist of the Powder and Acquisition Drill System (PADS), the Dust Removal Tool (DRT), and the Collection and Handling for Interior Martian Rock Analysis (CHIMRA). CHIMRA is a device which can collect particular (unconsolidated – dirt) from the surface, or from trenches created by the wheels, as well as collecting material created with PADS. Internal to CHIMRA are mechanisms to sieve and sort particulates, separate them by particulate size, and separate samples into the correct volume required by the different instruments, and then deliver the sorted samples to the instrument into the instrument inlets. PADS is a combination of drill and hammer, which can drill and hammer rocks into powder, collect the powdered rock and transfer it to CHIMRA. It is also capable of

changing its own drill bit from a box of spare bits mounted on the rover chassis. PADS is a rotating brush system that can be used to clean a rock surface, and to clean samples from the observation tray. Finally, there is the Organic Check Material (OCM) also mounted on the rover chassis. This consists of a set of sealed bricks containing synthetic organic materials (that are not found to be naturally occurring) in an inorganic matrix. By using SA/SPaH to sample the OCM bricks, the effect of the sampling process on organic materials in the samples can be calibrated.

5.4. The Payload

To meet the science objectives of MSL, ten instruments were chosen to fly. The Instrument types are broken out by those mounted on the RSM, contact instruments on the turret of the SA/SPaH, the analytical laboratories, and the environmental characterization instruments (Fig. 10.) The remote sensing instruments include the ChemCam and the MastCam. The ChemCam is a laser-induced-breakdown spectrometer and remote micro imager able to determine elemental composition and geomorphologic context, and the MastCam is a color stereo imager. The contact instruments include the Mars Hand Lens Imager (MAHLI), which is a microscopic imager, and the Alpha Particle X-Ray Spectrometer for determination of elemental chemistry. The analytical laboratories include the Sample Analysis at Mars (SAM) instrument and the Chemistry and Mineralogy (CheMin) instrument. SAM uses gas extraction through high heat to measure the chemical constituents of volatiles taken from Martian regolith samples. CheMin uses powder X-ray Diffraction to look at the mineralogy of powdered samples to see how the material interacted with water in the past. The environmental characterization instruments include the MARs Descent Imager (MARDI,) the Rover Environmental Monitoring Station (REMS,) Radiation Assessment Detector (RAD) and the Dynamic Albedo of Neutrons (DAN) instrument. MARDI is a fixed-focus color camera that acquires five images per second from heat shield separation to touchdown. Its purpose is to identify exactly where the rover landed and provide geologic context. REMS provides measurements of wind speed and direction, pressure, relative humidity, air temperature, ground temperature and ultraviolet radiation. RAD is an energetic particle detector designed to analyze the full energetic particle radiation spectrum of the Martian surface. Finally, DAN is an active and passive neutron spectrometer used to measure the abundances and depth of H- and OH-materials (water bearing) to a depth of one meter.

6. THE MSL POWER SYSTEM

The MSL Power System is comprised of:

1. Power Assemblies (three)
 - a. Cruise Power Assembly (CPA)

- b. Descent Power Assembly (DPA)
 - c. Rover Power Assembly (RPA)
2. Power Analog Modules (three)
 - a. Cruise Power Analog Module (CPAM)
 - b. Descent Power Analog Module (DPAM)
 - c. Rover Power Analog Module (RPAM)
3. Pyro Firing Assemblies (two)
 - a. Descent Stage – Located within the DPA.
 - b. Rover Pyro Firing Assembly (RPFA)
4. Shunt Radiator (two)
 - a. Cruise Shunt Radiator
 - b. Rover Shunt Radiator
5. Power Sources
 - a. Cruise Solar Arrays
 - b. MMRTG
 - c. Batteries
 - i. Descent Stage Thermal Batteries
 - ii. Descent Stage Pyro Thermal Batteries
 - iii. Rover Secondary Batteries

A block diagram of the MSL Power System Architecture is shown in Fig. 11.

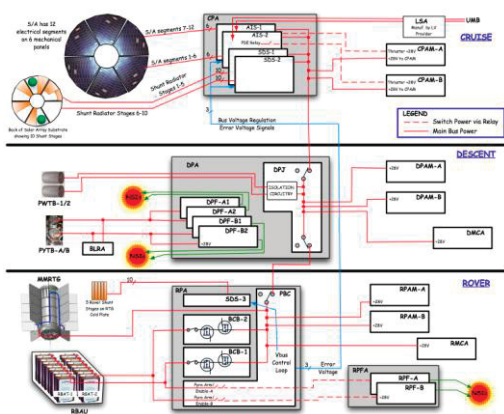


Figure 11. The MSL Power System Architecture.

During launch and cruise, the spacecraft power system encompasses the power system components of the cruise stage, the descent stage, and the rover, and incorporates multiple power technologies. The cruise stage has a 1.6kW solar array composed of six panels, each containing two segments, with each segment comprised of 21 strings of 15 28.5% efficient BTJ cells. The Descent Stage has two thermal batteries; one for power and regulation of the power bus during EDL and the other to power the pyro bus of the Descent Stage. Finally, the rover has an 110W MMRTG (multi-mission radioisotope thermal generator) power source, and two 43A-h large-cell Li-ion batteries.

The power system design is extremely versatile, capable of managing the bus while powered from the solar array, MMRTG, and rover batteries during cruise, utilizing power from thermal batteries during EDL, and operating with only the MMRTG and battery during surface operations. The MSL power system is unique

both in the way it is distributed across the spacecraft rover, descent and cruise stages, and also in that it is the first RPS-based rover flown by NASA. The MMRTG and rover batteries are connected to the bus during all mission phases. Although the MMRTG remains on the bus throughout the mission, it is the primary energy source only during surface operations and during the approximately 80 minutes following launch, when power is provided to the entire spacecraft by the MMRTG and the rover batteries. This is a driving case for sizing the rover batteries.

During cruise, power is mainly provided by the cruise stage solar array. The six panels are an integral part of the structure of the cruise stage. The solar array uses a switching control design managed by two solar array interface slices (AIS) each capable of independently switching six of the 12 circuits, and two shunt driver slices (SDS). The shunt radiators are incorporated into the cruise structure on the back of the solar array panels. Bus voltage is managed by the 800W linear shunt regulator with segments switched in as needed to maintain power levels. Power from the array is provided to the shared bus across the spacecraft, and bus voltage and stability are managed by the power bus controller (PBC) in the rover. Just before the cruise stage is separated from the landing system, the descent stage thermal batteries are activated, and the cruise stage is disconnected from the bus by dead-face relays in the Descent Power Junction (DPJ,) at which point the cruise stage is unpowered and separates from the rest of the spacecraft. The cruise stage also incorporates the CHRS needed to remove thermal energy generated by the MMRTG that is not needed during cruise.

During descent, power is provided by the Descent Stage thermal batteries, consisting of two 27—37V batteries for the power bus and two 26—36V batteries dedicated to pyro initiation. The thermal batteries also control the bus voltage. Both power bus batteries are required, i.e., they are not redundant. The pyro thermal batteries are each separately dedicated to the A or B side redundant pyro buses. Once the rover has been landed by the descent stage, dead-face relays in the DPJ are again used to separate the descent power bus from the rover power bus, and the descent stage operates with the thermal batteries during the brief time it requires to fly away from the rover and “land.”

After descent, the rover only receives the approximately 110W (BOL) continuous electrical power from the MMRTG to operate the flight system. The rover utilizes a linear shunt driver based on the SDS to manage bus voltage. MMRTG power is used to charge the rover’s two Li-ion batteries, which are the primary source of electrical power for operations. Rover power utilization ranges from 45—70W while sleeping, to approximately 150W minimum when awake, up to greater than 500W peak while “roving” or moving.

Besides power sourcing and management, the power system also contains the pyro firing circuitry in the PFA on the Rover and within the DPA on the Descent Stage and power switch capabilities in the PAMs. Pyro initiation is handled on the descent stage for EDL and on the Rover for surface deployments. There are a total of 90 pyro firing events requiring 180 NASA Standard Initiator firings.

7. SUMMARY

The complex science, engineering, and schedule requirements of the mission have resulted in a number of firsts for a NASA Mars Rover: It is the first fully redundant and cross-strapped rover system. It is the first RTG powered rover system. It is the first “soft landing” rover system. It is the first rover capable of traversing 20 km. And it is the first rover with a *required* minimum lifetime of 687 Martian Days (Sols).

These “firsts” have pushed the engineers of the Jet Propulsion Laboratory (JPL) to be extremely creative. Compared to past Mars Rovers, MSL is far reaching. Just how far reaching can be seen in Tab. 2.

Table 2. NASA Mars Rovers Comparison.

Requirement	MSL	MER	Sojourner
Driving Distance	20 km	0.6 km	N/A
Mission Lifetime	687 Sols	90 Sols	7-30 Sols
Number of Instruments	10	8	1
Payload Mass	80 kg	5 kg	1 kg
Rover Mass	930 kg	175 kg	10.5 kg
Power Generation	115 W (Nuclear)	140 W (Solar)	13 W (Solar)

The MSL requirements for driving distance, mission lifetime, the mass of ten science instruments on a rover far exceed anything done by Sojourner (Mars Pathfinder) or MER. The sheer size of the rover (Fig. 12), coupled with the high relative elevation and wide latitude range requirement, have lead the MSL engineering team to move away from the heritage airbag landing systems of MPF and MER, and to the invention and development of the “sky crane” soft landing system. Further, this new soft landing system drove the design of a new distributed, modular, and separable power system. Finally, the one year Martian lifetime requirement, the driving distance requirement, and the need to potentially operate at high latitudes, drove architects away from a purely solar power based design and to the use of an MMRTG.

The priorities of the Mars science community and the objectives of NASA’s Mars Exploration Program have driven the MSL engineering and instrument teams to develop *in situ* sample acquisition and analysis systems and instruments that far exceed those of any other NASA Mars landed mission.



Figure 12. NASA Mars Rovers – Size Comparison.

All of these reasons have made MSL the largest, most complex, and most capable rover NASA has ever endeavoured to build.

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